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## Shock Wave Data for Rocks

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### 1. INTRODUCTION

Shock wave equation of state data for rocks is the primary physical starting point for calculation of the effect of meteorite impact and explosions on the surfaces or in the crusts of the earth, moon, and other terrestrial planets [2,3,12,25,32,37,38,39,40,43], and primitive bodies such as comets and asteroids [9,54].

### 2. EQUATIONS OF STATE

Rocks are, by definition, composed of one or more minerals, and hence largely their equation of state behavior (Table 1) reflects the behavior of their constitutive minerals. The Hugoniot of rocks demonstrate the same regimes as sketched in Figure 3 of Sect. 2-6b.

Dynamic yielding behavior for porous rock, like ceramics which have been more extensively studied, reflect both the Hugoniot elastic limit of the porous mineral aggregate, as well as the porous rock. [15,46].

(NASA-CR-197639) SHOCK WAVE DATA  
FOR ROCKS (California Inst. of  
Tech.) 20 p

N95-70536

Unclass

Z9/16 0038417

Mixture theories are quite successful in synthesizing the Hugoniots of rocks from knowledge of the equations of state of constituent minerals.

For silicate rocks, Telegin et al. [47] have demonstrated good agreement between the observed Hugoniot and the calculated Hugoniot based upon an oxide mixture model. According to this model,

$$C_0 = a_{00} + a_0 \rho_0 + \sum_i a_i Z_i \quad (1a)$$

$$S = b_{00} + b_0 \rho_0 + \sum_i b_i Z_i \quad (1b)$$

where  $\rho_0$  is the initial density,  $Z_i$  is the mass fraction of component oxide  $i$ , and  $a_{00}$ ,  $a_0$ , the  $a_i$ 's,  $b_{00}$ ,  $b_0$ , and the  $b_i$ 's, are constants. This approach works well in the high pressure regime (4, of Figure 3, Sect. 2-6b). More successful over the pressure range of the entire Hugoniot is the mineral mixture model [8].

$$V(P) = \sum_i V_i(P) M_i \quad (2)$$

where  $V_i$  is the volume of constituent mineral,  $i$ , at pressure  $P$  and  $M_i$  is the mass fraction of mineral,  $i$ . Using the Rankine-Hugoniot equations,  $U_S$  and  $U_P$  are computed from the resulting P-V relation. Additional examples of construction of a theoretical Hugoniot from constituent minerals are given in [6] and [4].

*Acknowledgments.* Research supported by NSF, NASA, and DoD. Contribution #5333, Division of Geological and Planetary Sciences, California Institute of Technology.

TABLE 1. Equations of State of Rocks

Rock Name	Locality, Comments	Sample Density (Mg/m <sup>3</sup> )	C <sub>0</sub> (km/sec)	error ΔC <sub>0</sub> (km/sec)	S	error ΔS	lower U <sub>p</sub> (km/sec)	upper U <sub>p</sub> (km/sec)	Phase*	No. of Data	References
Albitite	Sylmar, PA	2.610	5.42	0.09	0.09	0.10	0	1.287	2	3	
			4.83	0.05	0.51	0.03	1.287	2.017	3	4	
			2.73	0.17	1.49	0.05	2.017	3.903	4	8	[11,33,35,53]
Andesite	Amchitka Is., Alaska	2.59	3.60 1.7	0.08 1.0	0.98 1.8	0.05 0.3	0.45 2.49	2.49 3.16	2 4	9 4	[10]
Anorthosite	Lunar 60025	2.229	2.02	0.10	1.57	0.03	2.036	5.196	2	11	[28,29]
Anorthosite	a	2.774	5.73 3.2 4.45	0.07 0.5 0.15	0.07 1.46 1.23	0.08 0.13 0.01	0 1.99 4.99	1.99 4.99 28.65	1 2 4	15 19 7	[3,5,11,13,14,33,35,53]
Basalt	low density <sup>b</sup>	2.793	5.80 4.2 2.4	0.15 0.2 0.2	-1.2 0.71 1.60	0.3 0.12 0.06	0.291 0.79 2.1	0.79 2.1 5.94	1 2 4	4 6 14	[5,30,52]
Basalt	high density <sup>c</sup>	3.200	4.96 4.09	0.14 0.15	0.88 1.35	0.10 0.04	0.385 1.913	1.963 5.99	2 4	8 12	[1,6,48]
Molten basalt	synthetic An <sub>36</sub> Di <sub>64</sub> <sup>d</sup>	2.615	3.67 2.93 0.8	- 0.15 0.4	0.19 1.46 2.6	- 0.13 0.2	0.44 0.65 1.72	0.65 1.72 2.06	1 2 4	2 4 3	[42]

TABLE 1. Equations of State of Rocks (continued)

Rock Name	Locality, Comments	Sample Density (Mg/m <sup>3</sup> )	C <sub>0</sub> (km/sec)	error ΔC <sub>0</sub> (km/sec)	S	error ΔS	lower Up (km/sec)	upper Up (km/sec)	Phase*	No. of Data	References
Molten basalt	Komatiite <sup>e</sup>	2.745	3.13	0.02	1.47	0.02	0.47	2.1	2	12	[36]
Volcanic Breccia	Amchitka Is., Alaska	1.82	-0.5	-	3.2	-	1.1	1.22	1	2	
			3.3	-	0.0	-	1.22	1.44	3	2	
			-1.1	-	3.1	-	1.44	1.65	2	2	
			1.9	0.2	1.2	0.9	1.65	3.25	4	3	[10]
Bronzitite	Bushveld, Transvaal	3.296	6.28	0.08	0.56	0.05	0.485	2.147	2	7	
			4.3	0.2	1.45	0.08	2.147	3.08	3	4	[11,33,35,53]
Bronzitite	Stillwater, Montana	3.277	5.99	-	1.56	-	0	0.483	1	2	
			6.47	0.06	0.60	0.04	0.483	2.131	2	25	
			5.16	0.07	1.17	0.03	2.043	3.481	3	21	[11,33,35,53]
Bronzitite	Pyroxenite (unspecified)	3.29	6.26	0.19	0.96	0.14	0.6	1.74	1	3	
			8.35	-	-0.21	-	1.74	2.26	2	2	
			5.1	0.2	1.30	0.07	2.26	5.8	3	4	[48]
Chalk	Dover, England	1.365	1.0	0.7	1.5	0.7	1.414	1.959	2	4	[50]
Chalk	(unspecified)	1.705	1.15	0.12	1.60	0.04	1.65	4.34	2	5	[31]
Chalc	(unspecified)	2.02	1.74	0.06	1.61	0.02	1.51	4.18	2	5	[31]
Chalk	moist	2.2	2.68	0.06	1.49	0.02	0.89	3.61	2	5	[31]
Clay	f	1.457	1.86	0.17	0.97	0.07	1.04	3.54	2	9	[23]
Clay	not given; 4% water	2.15	2.52	-	0.71	-	0.005	0.96	1	2	
			1.86	0.09	1.36	0.04	0.96	3.32	2	3	[7]

TABLE 1. Equations of State of Rocks (continued)

Rock Name	Locality, Comments	Sample Density (Mg/m <sup>3</sup> )	C <sub>0</sub> (km/sec)	error ΔC <sub>0</sub> (km/sec)	S	error ΔS	lower U <sub>p</sub> (km/sec)	upper U <sub>p</sub> (km/sec)	Phase*	No. of Data	References
Clay	not given; 4-20% water <sup>g</sup>	2.11	1.8	0.2	3.1	0.7	0.127	0.42	1	4	
			2.69	0.11	1.30	0.05	0.42	3.28	2	12	
			1.9	0.2	1.55	0.06	3.26	4.37	4	3	[7,24]
Diabase	h	3.00	4.89	0.11	1.20	0.15	0	0.915	2	6	
			5.68	0.06	0.25	0.05	0.843	1.758	3	14	
			3.61	0.07	1.41	0.02	1.713	3.727	4	21	[11,33,35,53]
Olivine Diabase	not given	3.13	6.8 4.9	- 0.3	0.1 1.22	- 0.07	0.61 1.45	1.45 5.92	3 4	2 4	[35,48]
Dolomite	i	2.828	6.2	0.5	0.4	0.5	0.495	1.15	1	5	
			5.30	0.10	1.16	0.03	1.12	5.32	2	19	[31,45,52]
Dunite	low density <sup>j</sup>	3.262	6.38 4.82	0.09 0.16	0.81 1.33	0.06 0.05	0 2.399	2.4 5.95	2 4	55 29	[11,21,27,33, 34,35,48,53]
Dunite	high density <sup>k</sup>	3.791	5.5 6.35 4.0	0.2 0.11 0.2	1.8 0.49 1.47	0.4 0.07 0.08	0 0.701 2.429	0.701 2.429 3.407	2 3 4	3 18 13	[11,33,34,35, 53]
Eclogite	l	3.480	5.55 - 6.34	0.14 0.06	2.0 0.92	0.3 0.03	0 0.714	0.73 3.305	1 4	7 45	[33,34,35,53]
Feldspar Peridotite	not given	3.22	5.78 4.59	- 0.06	0.93 1.373	- 0.014	1.4 2.73	2.73 5.84	2 4	2 3	[48]

TABLE 1. Equations of State of Rocks (continued)

Rock Name	Locality, Comments	Sample Density (Mg/m <sup>3</sup> )	C <sub>0</sub> (km/sec)	error ΔC <sub>0</sub> (km/sec)	S	error ΔS	lower U <sub>p</sub> (km/sec)	upper U <sub>p</sub> (km/sec)	Phase*	No. of Data	References
Gabbro	m	2.941	6.4	0.7	0.2	1.4	0.286	0.608	1	5	
			8.1	0.2	-2.6	0.3	0.515	0.878	2	9	
			5.8	0.2	-0.64	0.19	0.864	1.677	3	13	
			3.3	0.3	1.41	0.10	1.629	3.059	4	17	[27,33,35]
Enstatite Gabbro	not given	3.15	4.98	0.14	1.28	0.04	1.44	5.88	2	4	[48]
Gneiss	n	2.79	5.30	-	0.20	-	0.704	1.788	1	2	
			2.68	0.19	1.54	0.04	1.788	6.047	2	10	[45]
Granite	o	2.657	5.6	0.2	-0.2	0.3	0	1.00	1	21	
			4.88	0.13	0.41	0.09	0.945	2.044	2	27	
			2.06	0.17	1.66	0.05	2.034	6.01	4	58	[10,23,33,34, 35,52,53]
Granodiorite	p	2.664	5.879	0.015	0.383	0.017	0.2	3.191	1	14	
Jadeite	Burma	3.335	6.41	0.06	1.30	0.08	0	1.005	1	3	
			6.57	0.10	1.09	0.07	0.986	1.94	2	8	
			7.44	0.12	0.64	0.04	1.94	3.434	3	8	[33,34,35,53]
Limestone	Salisbury Plane, England	1.742	0.00	0.18	2.61	0.15	0.56	1.67	2	10	
Limestone	q	2.286	2.24	0.15	1.18	0.06	1.51	3.8	4	11	[52]
			1.8	0.2	2.11	0.18	0.789	1.62	2	7	
			2.6	0.2	1.43	0.07	1.62	5.05	4	7	[5,30]

TABLE 1. Equations of State of Rocks (continued)

Rock Name	Locality, Comments	Sample Density (Mg/m <sup>3</sup> )	C <sub>0</sub> (km/sec)	error ΔC <sub>0</sub> (km/sec)	S	error ΔS	lower U <sub>p</sub> (km/sec)	upper U <sub>p</sub> (km/sec)	Phase*	No. of Data	References
Limestone	r	2.597	6.7	0.8	-16	7	0.036	0.163	1	4	
			3.70	0.13	-1.0	0.5	0.163	0.387	3	3	
			2.67	0.17	2.26	0.16	0.387	1.487	2	18	
			3.4	0.2	1.54	0.07	1.487	5.791	4	21	[5,10,23,45,50,52]
Marble	s	2.697	5.2	0.4	-2.8	1.6	0.086	0.43	1	8	
			3.71	0.10	1.48	0.08	0.43	2.56	2	16	[5,22,26,52]
Marble	t	2.841	5.4	0.3	1.14	0.18	0.913	3.08	2	10	[23]
Olivinite	not given	3.376	6.38	0.09	1.01	0.09	0.59	1.33	1	4	
			7.1	0.6	0.4	0.3	1.27	2.2	3	6	
			5.21	0.11	1.27	0.02	2.04	9.07	4	11	[48]
Pumice	u	0.55	0.31	-	1.06	-	2.32	2.96	2	2	
			-0.54	0.05	1.347	0.011	2.96	6.19	4	3	[30]
Quartzite	not given	2.65	4.72	0.09	1.24	0.17	0.25	0.79	1	4	
			5.621	0.006	0.062	0.004	0.79	2.05	2	4	
			2.3	0.3	1.59	0.07	2.05	6.18	3	4	
			4.32	0.06	1.258	0.006	6.18	12.37	4	5	[49]
Quartzite	v	2.648	6.13	0.02	0.05	0.02	0.135	2.7	2	45	[5,52]
Quartzite	w	2.646	5.43	0.10	1.0	0.3	0.174	0.54	1	9	[5,52]
Sand	x	1.61	1.70	0.08	0.46	0.08	0.5	0.86	1	12	
			1.0	0.4	1.7	0.3	0.82	1.72	2	14	
			2.1	0.2	1.10	0.09	1.71	3.88	4	16	[19,23,52]
Wet Sand	4% water <sup>y</sup>	1.72	1.61	0.14	1.26	0.06	1.14	3.49	2	5	
			-0.15	-	1.76	-	3.49	3.74	4	2	[52]

TABLE 1. Equations of State of Rocks (continued)

Rock Name	Locality, Comments	Sample Density (Mg/m <sup>3</sup> )	C <sub>0</sub> (km/sec)	error ΔC <sub>0</sub> (km/sec)	S	error ΔS	lower U <sub>p</sub> (km/sec)	upper U <sub>p</sub> (km/sec)	Phase*	No. of Data	References
Wet Sand	10% water <sup>y</sup>	1.84	1.79	-	1.45	-	1.11	1.98	2	2	
			3.05	-	0.82	-	1.98	2.79	3	2	
			0.8	0.3	1.62	0.10	2.79	3.44	4	3	[52]
Wet Sand	19% water <sup>y</sup>	1.96	2.75	0.14	1.11	0.07	1.01	2.71	2	6	
			1.2	0.4	1.68	0.12	2.67	3.52	4	6	[52]
Wet Sand	z	1.985	3.39	0.08	1.14	0.05	0.98	1.94	2	4	[23]
Sandstone	aa	1.993	3.11	0.16	-1.7	0.5	0.058	0.508	1	20	
			1.58	0.09	1.49	0.07	0.472	2.041	2	23	
			2.9	0.6	0.8	0.3	1.70	2.18	3	7	
			0.57	0.14	1.63	0.03	2.57	6.43	4	11	[5,44]
Serpentine	bb	2.621	5.30	0.15	0.90	0.11	0.431	2.025	2	10	
			6.5	0.4	0.20	0.18	1.719	2.561	3	10	
			3.8	0.5	1.34	0.12	2.658	5.427	4	16	[11,33,51,53]
Shale	cc	2.545	1.6	0.3	5.3	0.5	0.104	0.72	1	29	
			3.85	0.17	1.38	0.16	0.656	1.39	3	33	
			4.56	0.11	0.79	0.05	1.388	2.832	2	63	
			2.3	0.3	1.61	0.09	2.821	3.877	4	38	[7,18,24,33,41]
Oil Shale	dd	2.239	3.66	0.07	1.18	0.03	0.663	2.812	2	51	
			7.1	0.5	-0.04	0.16	2.802	3.108	3	6	
			3.3	0.4	1.28	0.12	3.091	4.343	4	30	[10,16,17,33]
Soil (peat)	not given	0.32	0.00	-	1.66	-	0.5	1.5	2	-	[20]
Tuff	low density <sup>ee</sup>	1.298	1.18	0.10	1.25	0.04	0.95	3.653	2	38	
			5.4	0.6	0.04	0.18	3.344	4.061	3	6	
			0.9	1.3	1.3	0.3	4.057	5.52	4	15	[10,23,33]

TABLE 1. Equations of State of Rocks (continued)

Rock Name	Locality, Comments	Sample Density (Mg/m <sup>3</sup> )	C <sub>0</sub> (km/sec)	error ΔC <sub>0</sub> (km/sec)	S	error ΔS	lower U <sub>p</sub> (km/sec)	upper U <sub>p</sub> (km/sec)	Phase*	No. of Data	References
Tuff	medium density <sup>ff</sup>	1.610	1.29	0.12	1.43	0.04	1.026	5.19	2	27	[10,23,33]
Tuff	high density <sup>gg</sup>	1.851	2.45	0.19	1.13	0.10	0.78	2.82	2	74	
			1.7	0.3	1.48	0.06	2.79	6.50	4	57	[10,23,33,45]

\*Phases: 1) Elastic shock; 2) Low pressure phase; 3) Mixed region; 4) High pressure phase.

<sup>a</sup>Tahawus, NY; San Gabriel Anorthosite, CA; Apollo 15,418; "gabbroic anorthosite", locality unspecified; Agua Dulce Canyon, CA

<sup>b</sup>Vacaville basalt, Mt. Vaca Quad. CA; locality unspecified; Nevada Test Site, NV

<sup>c</sup>Terrestrial dolerite - locality not given; lunar basalt 70215

<sup>d</sup>Starting temperature 1673 K

<sup>e</sup>Synthetic: matching komatiite from Munro Township, Ontario; starting temperature 1773 K

<sup>f</sup>Lakebed Area 5, Nevada Test Site, NV

<sup>g</sup>not given; 4-20%-water; also site U2, Nevada Test Site, Nye Co. NV

<sup>h</sup>Centreville, VA; Frederick, MD

<sup>i</sup>Hole U10B, Nevada Test Site, NV; Banded Mtn., Nevada Test Site, NV; Ferris Wheel Dolomite, Nevada Test Site, NV; not given

<sup>j</sup>Jackson County, NC; Twin Sisters Peaks, WA; not given

<sup>k</sup>Mooihoek Mine, Transvaal

<sup>l</sup>Healdsburg, CA; Sunnmore, Norway

<sup>m</sup>Bytownite gabbro, Duluth, MN; San Marcos, Escondido, CA

<sup>n</sup>Rock Cove, Nevada Test Site, Nevada

<sup>o</sup>near Lithonia, GA; near Shoal Nuclear Detonation, Fallon NV; near area 15, Nevada Test Site, Nevada

<sup>p</sup>Hardhat; Climax Stock Granodiorite, Nevada Test Site, NV

<sup>q</sup>Kaibab Limestone, AZ; Spergen Limestone, Bedford, IL

<sup>r</sup>Solenhofen, Bavaria; Banded Mountain limestone, Nevada Test Site, NV

<sup>s</sup>Yule Marble, Gunnison City, CO; Vermont Marble, West Rutland, VT; not given

<sup>t</sup>Area 15, Nevada Test Site, NV

<sup>u</sup>U. S. Pumice Mine, Mono Craters, Lee Vining, CA

<sup>v</sup>Novaculite, Arkansas

<sup>w</sup>Eureka quartzite, Confusion Mountain, nr. Ely, NV

<sup>x</sup>synthetic SiO<sub>2</sub>; Ottawa banding sand, Ottawa IL, at -10°C; oven furnace sand (silica sand); not given

<sup>y</sup>Ottawa banding sand, Ottawa IL at -10°C

<sup>z</sup>Oven furnace sand (silica sand), locality not given

<sup>aa</sup>Coconino sandstone, Flagstaff, AZ; Massillon sandstone, Glenmont, OH; St. Peters sandstone, Klondike, MO

<sup>bb</sup>Ver-myen, Italy; antigorite, Thurman NY; chrysotile, Quebec

<sup>cc</sup>Gas shale, Devonian, Lincoln Co., WY; clay shale, locality not given; shales, Site U2, Nevada Test Site, Nye Co., NV

<sup>dd</sup>Green River, Rifle CO; Laramie oil shale; Mahogany ledge oil shale

<sup>ee</sup>Areas 3, 12, 16, buff Rainier Mesa Tuff, white Rainier Mesa Tuff, and unspecified, Nevada Test Site, NV

<sup>ff</sup>Areas 3, 12, 16, pink Rainier Mesa Tuff, and unspecified, Nevada Test Site, NV

**88Rainier Mesa Tuff, Areas 3, 12, 16, Pahute Mesa Tuff, and unspecified, Nevada Test Site, NV**

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